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N42.31

American National Standard for Measurement Procedures for Resolution and Efficiency of Wide-Bandgap Semiconductor Detectors of Ionizing Radiation

Accredited by the American National Standards Institute

Sponsored by the
National Committee on Radiation Instrumentation, N42

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Accredited by the

American National Standards Institute

Secretariat

The Institute of Electrical and Electronics Engineers, Inc.

Approved 20 February 2003

American National Standards Institute

Abstract: Standard measurement and test procedures are established for wide-bandgap semiconductor detectors such as cadmium telluride (CdTe), cadmium-zinc-telluride (CdZnTe), and mercuric iodide (HgI_2) that can be used at room temperature for the detection and quantitative characterization of gamma-rays, X-rays, and charged particles. Standard terminology and descriptions of the principal features of the detectors are included. Included in this standard is an annex on interfering electromagnetic noise, which is a factor in such measurements.

Keywords: cadmium telluride, cadmium zinc telluride, CdTe, charged particle, CZT, electron-hole pair, gamma rays, HgI, ionizing radiation, ion pair, MCA, mercuric iodide, multichannel analyzer, semiconductor detector, X-ray

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Introduction

(This introduction is not part of ANSI N42.31-2003, American National Standard for Measurement Procedures for Resolution and Efficiency of Wide-Bandgap Semiconductor Detectors of Ionizing Radiation.)

This standard is the responsibility of the Accredited American Standards Committee on Radiation Instrumentation, N42. The standard was approved on N42 letter ballot of 10 July 2002.

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American National Standard for Measurement Procedures for Resolution and Efficiency of Wide-Bandgap Semiconductor Detectors of Ionizing Radiation

1. Overview

1.1 Scope

This standard applies to wide-bandgap semiconductor radiation detectors, such as cadmium telluride (CdTe), cadmium-zinc-telluride (CdZnTe, referred to herein as CZT), and mercuric iodide (HgI_2) used in the detection and measurement of ionizing radiation at room temperature; gamma rays, X-rays, and charged particles are covered. The measurement procedures described herein apply primarily to detector elements having planar, hemispherical, or other geometries in which charge carriers of both polarities contribute to the output signal. When the devices are an integral part of a system, it may not be possible for a user to make tests on the detector alone. In this instance, tests on the detector element must be established by mutual agreement between the manufacturer and the user.

1.2 Purpose

The purpose of this standard is to establish terminology and test procedures that have the same meaning to both manufacturers and users. Not all tests described in this standard are mandatory, but those used to specify performance shall be made in accordance with the procedures described herein. (Use of the word “shall” indicates a mandatory requirement, “must” a physical one, and “should” means “recommended.”)

1.3 Abbreviations

Abbreviations, defined in 3.3, are used liberally throughout this document.

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2. References

Standards referred to herein are listed below. The details of the test instruments and the test procedures described in two of the standards—IEEE Std 301™-1988 and IEEE Std 325™-1996—are closely related to those described in this document and are recommended as adjuncts to it.

DOE Report DOE/ER-0457T (May 1990), Standard NIM Instrumentation System.[1]

IEEE Std 194™-1977, IEEE Standard Pulse Terms and Definitions.[2,3,4]

IEEE Std 300™-1988 (Reaff 1993), IEEE Standard Test Procedures for Semiconductor Charged-Particle Detectors.

IEEE Std 301-1988, IEEE Standard Test Procedures for Amplifiers and Preamplifiers used with Detectors of Ionizing Radiation.

IEEE Std 325-1996, IEEE Standard Test Procedures for Germanium Gamma-Ray Detectors.

IEEE Std 759™-1984, IEEE Standard Test Procedures for Semiconductor X-Ray Energy Spectrometers.

IEEE Std 1160™-1993, IEEE Standard Test Procedures for High-Purity Germanium Crystals for Radiation Detectors.

3. Definitions, symbols, and abbreviations

3.1 Definitions

Specialized terms used in this standard plus some others that are relevant appear in this subclause. Most of the technical terms within the definitions are themselves defined here but, with a few exceptions, are not cross-referenced. Terms used infrequently in the document are defined where they appear; they may or may not be defined in this subclause.

3.1.1 active region: A region of a detector in which charge created by ionizing radiation contributes significantly to the output signal.

3.1.2 amplifier: An electronic instrument for increasing the amplitude of a signal.

3.1.3 amplifier shaping time: A nonspecific indication of the shaped-pulse width issuing from a pulse amplifier.

3.1.4 amplifier time constant: A misnomer for the width of the shaped pulse issuing from a pulse amplifier. *See:* **shaping-time index ($t_{0.5}$).**

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[1]Available from Louis Costrell, NIM Committee Chairman, or Michael Unterweger, NIM Committee Vice-chairman, both at National Institute of Standards and Technology, Radiation Physics Division or from the National Technical Information Service, U.S. Dept. of Commerce, Springfield, VA 22161.

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[3]IEEE Std 194-1977 has been withdrawn; however, copies can be obtained from Global Engineering, 15 Inverness Way East, Englewood, CO 80112-5704, USA, tel. (303) 792-2181 (http://global.ihs.com/).

[4]IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (http://standards.ieee.org/).

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3.1.5 analog-to-digital converter (ADC): An instrument that digitally encodes electrical pulses according to their amplitudes. An ADC is usually part of a multichannel analyzer (MCA).

3.1.6 area (of all or part of a spectral line): The counts accumulated within a selected number of channels in a spectral line.

3.1.7 background: Unwanted counts that appear in a spectrum due to ambient radiation, to a test source containing emitters other than the desired ones, or to spectral distortions caused by pulse pile-up.

3.1.8 background (ambient): The spectrum of ionizing radiation observed when a test source is replaced by a blank which is identical to the test source except for the absence of radioactivity.

3.1.9 ballistic deficit (BD): The loss in signal amplitude that occurs when the charge collection time in a detector is a significant fraction of the amplifier's differentiating time constant.

3.1.10 bandgap: The energy difference between the bottom of the conduction band and the top of the valence band.

3.1.11 baseline (of an electrical pulse): The average of the levels from which a pulse departs and to which it returns in the absence of an overlapping pulse (IEEE Std 194-1977).

3.1.12 baseline restorer (BLR): A circuit that rapidly restores the baseline following an amplifier's output pulse (or train of pulses) to the level that existed before the pulse.

3.1.13 bias, detector: The voltage applied to a detector to produce the electric field that sweeps out the signal charge.

3.1.14 bias resistor: The resistor through which the bias voltage is applied to a detector.

3.1.15 bipolar pulse: A signal pulse having two lobes, one above and the other below the baseline. When produced by a linear filter network, the two lobes have the same area but not necessarily the same peak amplitude.

3.1.16 capacitance, detector: The electrical capacitance measured between terminals of the detector under specified conditions of bias and frequency and with the amplitude of the signal used for the capacitance determination being small compared with the bandgap of the semiconductor comprising the detector.

3.1.17 carrier: *See:* **charge carrier.**

3.1.18 center line: *See:* **peak center line.**

3.1.19 channel: Refers to the channels in a multichannel analyzer.

3.1.20 charge carrier: A mobile electron or hole.

3.1.21 charge collection time: The time required for a charge produced by an ionizing event to be collected at the terminal of a detector under the influence of the detector bias voltage.

3.1.22 charge-sensitive preamplifier: An amplifier, preceding the main amplifier, in which the output amplitude is proportional to the charge injected at its input and virtually independent of detector capacitance (IEEE Std 301-1988).

3.1.23 contact: A conducting area applied to the surface of a detector to make electrical contact with it.

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3.1.24 *CR* differentiator: A high-pass electrical filter section comprising a capacitor in series with the signal path followed by a resistor across the path.

3.1.25 $(CR)^m$-$(RC)^n$ shaping: In an amplifier, the pulse shape produced by *m CR* high-pass filter sections (differentiators) in conjunction with *n RC* low-pass filter sections (integrators), all with the same time constant. If the input signal is a step function and no other high-pass sections are in the signal path, the pulse shape is unipolar if $m = 1$, bipolar if $m = 2$. For unipolar pulses, the waveform is described by $Kt^n e^{-t/\tau}$, where *K* is a constant, *t* is time, and τ is the time constant of the differentiator.

3.1.26 dead layer: In a semiconductor detector, a layer (frequently associated with a contact region) in which no significant part of the energy lost by photons or particles can contribute to the resulting signal.

3.1.27 dead time: The interval during which the second of two events is lost or is recorded with an error in its amplitude.

3.1.28 decay time constant: In the absence of a low-pass network preceding the point of observation, the time for a single-exponential waveform to decay to the fraction 1/e of its original amplitude.

3.1.29 depletion region: A region in which the mobile charge-carrier density is insufficient to neutralize the net fixed charge density of donors and acceptors. In a diode-type semiconductor radiation detector, the depletion region is the active (sensitive) region.

3.1.30 depletion voltage: The voltage at which a junction detector becomes fully depleted.

3.1.31 detector element: The semiconductor crystal including its contacts.

3.1.32 detector, semiconductor radiation: A semiconductor device in which the production and motion of excess free carriers is used for the detection and measurement of incident particles or photons.

3.1.33 differentiator: A high-pass filter network (usually a *CR* section) in which the waveform of the output signal approximates the mathematical derivative of the input waveform.

3.1.34 discriminator: A circuit having a threshold below which signals applied to the input will not cause an output signal and above which the input signal will trigger an output having an amplitude independent of the input signal height.

3.1.35 efficiency: In ANSI N42.31-2003, the total counts in a specified peak, corrected for background, divided by the total number of photons or particles emitted from a test source located 25 cm from the surface of the detector, or if so specified, from the entrance window of the detector housing. (The fraction so obtained, multiplied by 100, becomes the percentage efficiency.)

3.1.36 energy resolution: The full width at specified fractions of the maximum amplitude of a peak in a spectrum (after subtracting the background under the peak) expressed in units of energy or as a percentage of the energy corresponding to that peak.

3.1.37 enhanced energy resolution: Quality of a spectrum that has been improved by means of electronic-circuit signal processing beyond that of the filter network normally a part of a conventional, commercially available main amplifier. In the sense used here, the term “enhancement” does not apply to detectors having special geometries designed to overcome some of the shortcomings of planar detectors.

3.1.38 fall time t_f (of a pulse): The interval on the last transition (IEEE Std 194-1977) between the 90% and 10% points (unless other levels are specified) with respect to peak height. *See:* **transition (of a pulse).**

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3.1.39 filter, filter network: An electrical network designed to improve the signal-to-noise ratio in an amplifier and to shape the pulse issuing from the preamplifier according to the needs of the instruments following the main amplifier.

3.1.40 Fraznoid: Miller electron-hole pair coherent oscillation

3.1.41 full-energy peak (in a spectrum of ionizing radiation): The distribution, after subtracting the background spectrum, of the measured intensity as a function of energy of a monoenergetic stream of photons or particles.

Note—X-rays that may appear with energies below that of the full-energy peak are regarded as part of the background.

3.1.42 full width at half maximum (FWHM): The full width of a distribution measured at half the vertical distance between the background and the top of the peak. For a normal distribution, FWHM = $2\sigma(2\ln 2)^{0.5}$ = 2.355 times the standard deviation σ. As indicators of tailing, other parameters are useful, such as full width at 1/4th and 1/10th maximum (FW.25M, FW.1M).

3.1.43 Gaussian: Refers to the shape of a normal distribution or, incorrectly, to the shape of the output pulse issuing from a class of filter networks that includes the $(CR)^m$-$(RC)^n$ shaper. *See also:* **normal distribution, quasi-Gaussian,** and **semi-Gaussian.**

NOTE—The term "Gaussian peak" is more appropriately called a peak exhibiting a normal distribution. Gauss, who derived the equation for it in 1809, was not the first to do so. He was predated by DeMoivre in 1735 and Laplace in 1774 [B3].

3.1.44 geometry, detector: The physical configuration of a detector element (e.g., planar, hemispherical).

3.1.45 high-purity germanium (HPGe): Germanium with a low, net electrically active, uncompensated defect concentration, usually less than 10^{10} cm^{-3}.

3.1.46 high-side area: The area of a spectral peak measured above the background, and between the peak center line and the peak's high-energy toe.

3.1.47 high-side counting efficiency: Same as **efficiency** except that only the counts in the high-side area of the peak are recognized.

3.1.48 high-side width at half maximum (HSWHM): The width of the high-energy side of a peak measured from the peak center line at half of the vertical distance between the background and the top of the peak. (If the ratio of FW.1M to FWHM is less than 2.0, the HSWHM is exactly half of the FWHM.)

3.1.49 inactive region (of a semiconductor radiation detector): A region of a detector in which the charge created by ionizing radiation does not contribute significantly to the output signal. *See:* **dead layer.**

3.1.50 integrated pulse: In the absence of qualifiers (such as *true integration*), a pulse that has passed through one or more integrators. *See:* **integrator.**

3.1.51 integrator: In ANSI N42.31-2003, the term refers to a low-pass RC filter section.

3.1.52 junction: The transition boundary between semiconductor regions of different electrical properties (for example: $n–n^+$, p–n, $p–p^+$ semiconductors, or between a metal and a semiconductor).

3.1.53 leakage current: In the absence of external ionizing radiation and at the operating bias, the total current flowing through or across the surface of the detector element.

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3.1.54 line (in a spectrum): A sharply peaked portion of a spectrum that represents a specific feature of the incident ionizing radiation. *See:* **resolution.**

3.1.55 linear filtering: Pulse shaping in which the parameters of the filter are invariant with time and amplitude. An example of a linear filter is a $CR\text{-}(RC)^n$ shaping network.

3.1.56 live time (of a system): That portion of the counting time during which the system is capable of accepting data.

Note—The counting time, without a qualifier, is the sum of the live and dead times.

3.1.57 low-side tail(ing): *See:* **tailing (in a spectrum).**

3.1.58 main amplifier (shaping amplifier): The section of amplifier following the preamplifier that contains the pulse-shaping networks. *See:* **filter, filter network.**

3.1.59 multichannel analyzer (MCA): An electronic instrument that sorts signal pulses according to their amplitude, thereby producing a spectrum of pulse heights. An analog-to-digital converter (ADC) is a part of such an instrument. The ADC digitally encodes the amplitudes of the original pulses. The resulting binary numbers are channel addresses. Each encoded pulse adds one to the number of pulses stored in the addressed channel. (Stated differently, each incoming pulse adds a single count to the channel whose address is the digitally encoded pulse amplitude.) An MCA may have a large number of channels, typically 16000 for high resolution spectra, but normally 2000 or so are used for these detectors.

3.1.60 NIM (nuclear instrument module): A standardized modular instrumentation system comprising instrument modules and bins as defined in DOE Report DOE/ER-0457T.

3.1.61 NIM bin: A housing for **NIM** modules that conforms to the requirements of DOE Report DOE/ER-0457T. It includes bussed connectors at the rear which mate with connectors on the modules to provide them with power.

3.1.62 noise line width: The width of a peak produced by the signal from an ideal, noise-free pulser when substituted for the peak produced by a radioactive test source.

3.1.63 normal distribution: A spectrum of random events characterized by $P(x) = [1/\sigma\sqrt{(2\pi)}]\exp{-(1/2)(x/\sigma)^2}$, where P(x) is the probability of occurrence and σ is its standard deviation (rms value). This is the shape of an ideal peak in a spectrum of monoenergetic ionizing radiation; it can be characterized by $y = \exp{-(1/2)[(x - x_o)/\sigma]^2}$, which has a maximum value $y = 1$ at $x = x_o$, and a value of $y = e^{-1/2} = 0.6053$ when $\sigma = 1$.

3.1.64 peak: Context sensitive—may refer to the maximum height of a pulse (as in *peak amplitude*) or to a spectral line. *See:* **full-energy peak (in a spectrum of ionizing radiation)** and **line (in a spectrum)**.

3.1.65 peak center line: (A) In a spectral line displayed in graphical form, the peak center line is the ordinate passing through the highest-intensity point of the peak; **(B)** if the peak appears as a histogram (MCA display), the ordinate is the one passing through the center of the channel with the highest count (unless otherwise defined in the text where the term is used); **(C)** if the peak appears as a histogram (MCA display) with the two center channels exhibiting equal counts, the ordinate is the one passing through boundary between the two channels.

3.1.66 peaking time t_p (of a pulse): The interval between (a) 1% of peak height on the first transition (IEEE Std 194-1977) and (b) the top center line. *See:* **top center line** and **transition (of a pulse).**

3.1.67 preamplifier: The input section of an amplifier chain, usually located close to the detector.

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3.1.68 pulse duration (at the baseline): The width of a pulse measured close to the baseline, typically at 1% of the peak height ($t_{.01}$).

3.1.69 pulser, precision: A pulse generator that can be set with a precision of at least ± 0.1% of full scale (which does not imply an absolute full-scale accuracy ± 0.1%).

3.1.70 pulse shaper: *See:* **filter, filter network.**

3.1.71 RC integrator: A low-pass electrical filter section comprising a resistor in series with the signal path followed by a capacitor across it.

3.1.72 resolution: Refers to the ability to separate closely spaced peaks in a spectrum. *See:* **full width at half maximum, high-side width at half maximum.**

3.1.73 quasi-Gaussian: Refers to a class of filter networks contained in a main amplifier that shapes the signal issuing from a preamplifier, or to the shape of such a signal pulse.

3.1.74 rise time t_r (of a pulse): The interval on the first transition (IEEE Std 194-1977) between 10% and 90% of the peak height unless other levels are specified. *See:* **transition (of a pulse).**

3.1.75 semiconductor: Material in which the conductivity is due to charge carriers of both signs (electrons and holes), is normally in the range between metals and insulators, and in which the charge-carrier density can be changed by external means.

3.1.76 semiconductor, compensated: A semiconductor in which one type of impurity or imperfection (for example: donor) partially cancels the electrical effects of the other type of impurity or imperfection (for example: acceptor).

3.1.77 semi-Gaussian: Incorrect term for quasi-Gaussian. *See:* **quasi-Gaussian.**

3.1.78 shaped pulse: The pulse shape produced by passing the output signal from the preamplifier (approximately a step function) through the pulse-shaping network (filter network) in the main amplifier (shaping amplifier).

3.1.79 shaping amplifier: *See:* **main amplifier (shaping amplifier).**

3.1.80 shaping network: *See:* **filter, filter network.**

3.1.81 shaping time (in an amplifier): *See:* **amplifier shaping time** and **shaping-time index.**

3.1.82 shaping-time index ($t_{0.5}$): In a main amplifier, the width of the shaped unipolar pulse measured at 50% of its peak height.

3.1.83 signal-to-noise ratio: In ANSI N42.31-2003, *signal* refers to peak signal and *noise* refers to rms noise.

3.1.84 source, radioactive: A radionuclide prepared in a form convenient for use in testing a detector or spectrometer.

3.1.85 spectral: In ANSI N42.31-2003, the adjectival form of the noun *spectrum.*

3.1.86 spectral line: *See:* **line (in a spectrum).**

3.1.87 spectrum, energy: A differential distribution of the intensity of radiation as a function of energy.

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3.1.88 standard deviation (absolute): The square root of N in an accumulation of N randomly occurring events.

3.1.89 standard deviation (relative): The absolute standard deviation, $\sqrt{N}$, normalized to N, i.e., relative standard deviation = $1/\sqrt{N}$.

3.1.90 step function: An electrical signal characterized (ideally) by an instantaneous increase in amplitude followed by a plateau of constant amplitude.

3.1.91 tail pulse: Refers to the output of a pulser in which the signal decays according to the function $\exp[-t/\tau]$, where τ is the decay time constant.

3.1.92 tailing (in a spectrum): Broadening of the lower region of a spectral peak which, ideally, should have the shape of a normal distribution. Usually, the broadening is asymmetrical.

3.1.93 timing: Refers to the time of occurrence of an event in a detector.

3.1.94 timing discriminator: A class of discriminators in which the initiation of the output signal is keyed in some way to the initiation of the ionizing event.

3.1.95 toe: The intersection with the baseline (or background) of the upper or lower boundary of a peak. The word toe may also be accompanied by the adjectives *low-side* or *high-side*, where *low* and *high* refer to energy or channel number.

3.1.96 top center line: In a pulse, the ordinate that passes through the top of the peak; in a flat-topped pulse, the ordinate that bisects the nominally flat-topped region (IEEE Std 194-1977). In a spectral line, the ordinate that passes through the point of highest intensity. *See also:* **peak center line.**

3.1.97 transition (of a pulse): The region of a pulse in which a major change in amplitude occurs, such as at the leading edge (first transition) or the final trailing edge (last transition) (IEEE Std 194-1977).

3.1.98 undershoot: The part of a pulse opposite in polarity to the initial lobe. The undershoot occurs after a crossing of the baseline by the second transition (IEEE Std 194-1977; IEEE Std 301-1988).

3.1.99 unipolar pulse: A signal pulse having a single lobe above (or below) the baseline.

3.1.100 wide-bandgap detector: A detector, such as CdTe or CdZnTe, with a bandgap wide enough to permit room temperature operation.

3.2 Symbols

A amperes

C electrical capacitance

C coulombs

C_c calibrated capacitor that couples a pulse generator to a circuit under test

C_f feedback capacitance in the charge-sensitive loop of a preamplifier

C_t total capacitance at the input of a preamplifier

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E energy of a particle or a photon

e charge of the electron, 1.602×10^{-19} C

ε average energy required to form one hole-electron pair in a semiconductor detector

F farads

I electric current

Q electric charge

R_d detector bias resistor

R_f feedback resistor in the charge-sensitive loop of a preamplifier

σ standard deviation

σ_{abs} absolute standard deviation

σ_{rel} relative standard deviation = $1/\sigma_{abs}$

$t_{0.5}$ shaping-time index: pulse width at 50% of peak height

t_p peaking time of a pulse, measured from 1% of peak height on the leading edge to the highest point of the pulse

$t_{.01}$ width of a pulse, measured from 1% of peak height on the leading edge to 1% of peak height on the trailing edge

t_r pulse rise time: 10%–90% of its peak value, measured on the leading edge

τ time constant

τ_d time constant for the decay of a pulse

t_f pulse fall time: 90%–10% of its peak value, measured on the trailing edge

V volts

Z atomic number

3.3 Abbreviations

The full definitions are given in 3.1.

BD ballistic deficit

BLR baseline restorer

CZT cadmium-zinc-telluride (CdZnTe)

e-h pair electron-hole pair

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E-M	electromagnetic
FET	field-effect transistor
FWHM	full width of a peak at half its maximum height above the background
FW.1M	full width of a peak at 1/10th its maximum height above the background
FW.25M	full width of a peak at 1/4th its maximum height above the background
HPGe	high-purity germanium
HS	high side
HSA	high-side area of a peak above the background
HSWHM	high-side width of a peak at half its maximum height above the background
MCA	multichannel analyzer (or multichannel pulse-height analyzer)
NIM	nuclear instrument module
P/Z	pole-zero
rms	root-mean-square
STP	standard temperature and pressure: 101.325 CPA and 0 degrees C
WBG	wide bandgap

4. Introduction

High efficiency in the detection of photons requires a material of high atomic number (Z) and high density. The high density also aids the efficient detection of particles. In the search for better resolution of gamma rays, high-purity germanium detectors (HPGe) were developed (IEEE Std 1160-1993). HPGe is a high atomic number, high density material, and it produces the best gamma-ray energy resolution of any of today's semiconductors, in large part because an energy ε of only 3 eV is sufficient to produce an electron-hole pair. However, the low bandgap of germanium requires cryogenic operation to adequately reduce the thermally generated background current. The cryostat is complex and expensive, and structural considerations prevent easy measurement of the emissions of heavy particles (such as alpha particles).

In a continuing search, wide-bandgap (WBG) materials were investigated: HgI_2, CdTe, and most recently, CdZnTe.[5] All have atomic numbers and densities greater than HPGe, and all have ε's ≥ 4.3. The bandgap is sufficiently wide to allow room-temperature operation with acceptably low thermally generated leakage current. However, the maximum volumes of the detectors fabricated from the newer materials have been limited to 10 cm^3 (1999) compared to above 1500 cm^3 for HPGe. In scanning arrays, the small size is acceptable (Bennett et al. [B1]; Bertolucci [B2]).[6]

[5]Development of CZT began in the Soviet Union in the 1970s. Because the crystal growing equipment and diagnostic facilities were inadequate, no usable detectors were made. In the U.S., government funding aided CZT development to the point where private industry took an interest. Currently (2001), CZT crystals are being produced and sold by several manufacturers.

[6]The numbers in brackets correspond to those in the bibliography in Annex A.

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5. Detector characteristics

Where the WBG materials fit into the family of detectors used for photon spectrometry is shown in Figure 1 (Lund et al. [B9]). The properties of the semiconductors used in currently available detectors (2001) are given in Table 1.

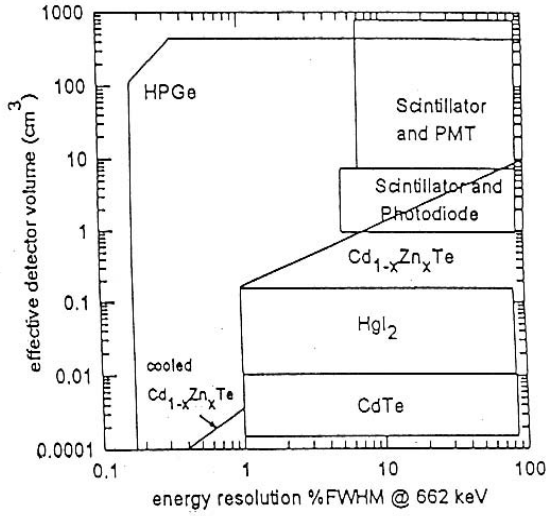


Figure 1—Photon detector characteristics

Table 1—Semiconductor Detector Characteristics[a]

Material @ 300 K or as noted	ε: eV per e-h pair	μ_e x 10^3 cm^2/V-s	μ_h x 10^3 cm^2/V-s	μ_e/μ_h	Z[b]	Dens.[c]	Max. Vol. (cm^3)	FWHM @ 662 keV
$Cd_{0.8}Zn_{0.2}Te$	5.0	1.400	0.1200	11.0	48/30/52	6.06	10	11.6
CdTe	4.4	1.100[d]	0.0750[e]	15.0	48/52	6.00	10 (?)	3.5[f]
HgI_2	4.3	0.075[g]	0.0042[h]	18.0	80/53	6.40	10	6.0
HPGe, 77 K	3.0	36.000	42.0000	0.9	32	5.33	500 (?)	0.9
Si	3.6	1.350	0.4800	2.8	14	2.33	?	—

[a]Knoll [B6] unless otherwise cited. (Knoll [B6] contains an extensive bibliography.)
[b]The Zs refer, respectively, to the elements of the compound.
[c]The density [B4] in g/cm^3 is given at the detector's indicated operating temperature.
[d]Figures for μ_e and μ_h were scaled from graphs given in Knoll [B6] and Scharagar [B13]. The numerical values given in Knoll [B6] and Scharagar [B13] are different from the scaled ones. The scaled figures are considered to be more nearly correct.
[e]See Footnote d.
[f]At 122 keV.
[g]See Footnote d.
[h]See Footnote d.

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5.1 Low-side tailing

The mobility-lifetime product $\mu\tau$ of WBG semiconductors is low compared with that of Ge and Si, making the carriers vulnerable to trapping. That, plus the ballistic deficit (BD) (see 3.1) that accompanies the collection of holes generated far from the cathode results in a loss of signal height that varies from event to event. This causes low-side tailing. The effects are especially noticeable in gamma-ray spectra obtained with a planar detector. The tailing, or lack of it, is shown in Figure 2 (Keele [B5]) and Figure 3 (Miko, Rawool-Sullivan [B11]).

a) Figure 2 shows the spectrum of a 662 keV ^{137}Cs gamma ray, the upper peak without resolution enhancement and the lower peak with enhancement.
b) Figure 3 shows the 32 keV x-ray peak that accompanies the gamma-ray peak.

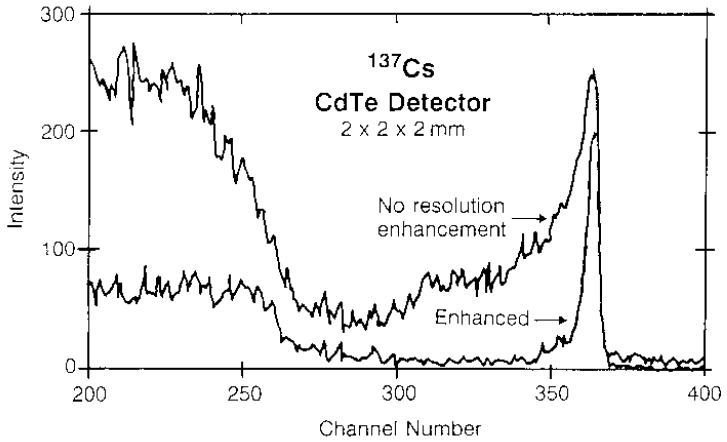


Figure 2—The 662 keV ^{137}Cs gamma-ray peak, CZT detector. Upper peak, without resolution enhancement; lower peak, with enhancement (Keele [B5]).

There are several ways of reducing a low-side tail. Some depend on signal processing by electronic circuits designed for the purpose (Keele [B5]; Lund et al. [B9]; Sakai et al. [B12]) and some other detector geometry other than planar (Lindgren et al. [B7]; Luke [B8]; McGregor [B10]; Tousignant [B14]). A signal processing technique was used to produce the lower peak in Figure 2 (Keele [B5]).

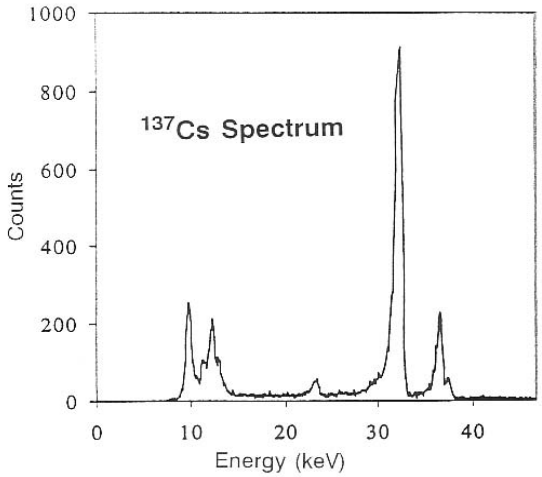


Figure 3—X-ray peaks, ^{137}Cs, CZT planar detector (Miko, Rawool-Sullivan [B11]). The peak at 32 KeV is the unresolved combination of peaks at 31.8 and 32.2 keV.

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The charge collection dynamics that lead to tailing are explained in 5.2.

5.2 Charge collection

An ionizing event in the active region of a semiconductor detector produces electron-hole pairs. The electrons drifting towards the anode and the holes towards the cathode comprise currents that charge the feedback capacitor C_f in the charge-sensitive preamplifier (IEEE Std 301-1988), in turn producing the preamplifier output signal. Its waveform depends upon several factors: where the initial ionization occurs within the active volume of the detector, the detector geometry, and the type of semiconductor.

The waveform dependence on the location of the initial ionization is shown in Figure 4 (Sakai et al. [B12]).[7] In all cases, the leading edge of the signal is due to electron drift, the trailing edge (slow portion) to hole drift.

a) In Waveform 1, the ionization occurs close to the cathode. The holes have a short distance to travel before collection; the electrons produce nearly all of the output signal. The duration of the leading edge of the waveform indicates an electron collection time of 0.5 μs.
b) In Waveform 3, the ionization occurs closer to the anode. Approximately half of the signal is due to the slowly moving holes. These have a drift time > 5 μs.
c) In Waveform 2, the location is intermediate between positions 1 and 3.
d) In Figure 2, where the ionizing events are gamma rays, charge can be generated anywhere within the detector; for the most part, the conditions described above in b) apply. The long collection time of the holes results in BD and trapping. The resulting signal loss varies from event to event, accounting for the tail in the unenhanced spectrum.
e) In the X-ray spectrum in Figure 3, all of the ionization occurs close to the cathode; the conditions described above in a) apply. Because of the rapid collection of the holes, BD and trapping are minimal, accounting for the low degree of tailing.

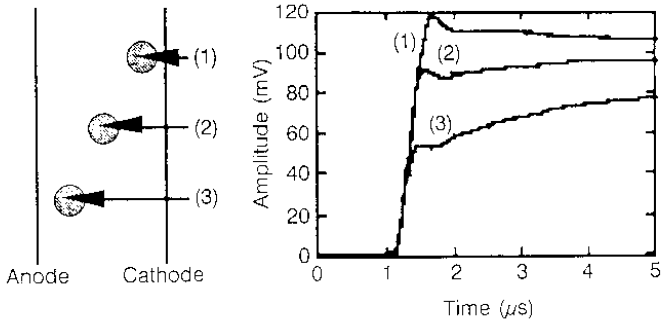


Figure 4—Preamplifier outputs for photons interacting with a planar detector: (1) near the cathode, (2) intermediate position, (3) near the anode (Sakai et al. [B12]).

The preceding supports the earlier comments about the tailing in Figure 2 and the lack of it in Figure 3.

It must be emphasized that a low-side tail is pronounced only when a WBG *planar* detector is used for the spectrometry of *gamma rays*, not when (1) X-rays or particles are being measured in which all of the holes are generated close to the cathode, and (2) not when geometries other than planar are used—geometries designed for the specific purpose of reducing the low-side tail.

[7]The detector used for the illustration was reported to be a cube of CZT, 5 x 5 x 5 mm irradiated by 662 keV gamma rays (Sakai et al. [B12]). The overshoots and sags in the slowly rising parts of the signals are probably artifacts of the electronics.

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5.3 Resolution and efficiency indicators

Traditionally, the measure of energy resolution has been the FWHM of a spectral line produced by a test source, and the measure of detector efficiency η has been the ratio of the counts recorded in the peak to those emitted from a source placed 25 cm from the detector (all measurements corrected for background). Contributing to the viability of these measurements is the symmetry of the peak, at least to the extent that the location of the low-side toe can be clearly defined (see 3.1). With the advent of WBG detectors, FWHM and counts within the peak continue to be the standards when both toes can be located, but when the low-side toe is obscured by tailing, the high-side width at half maximum (HSWHM) and high-side area (HSA) (see 3.1, 5.4) shall be the quantities associated with resolution and efficiency. How these are defined is shown in Figure 5, which is the spectrum of the unenhanced peak of Figure 3.

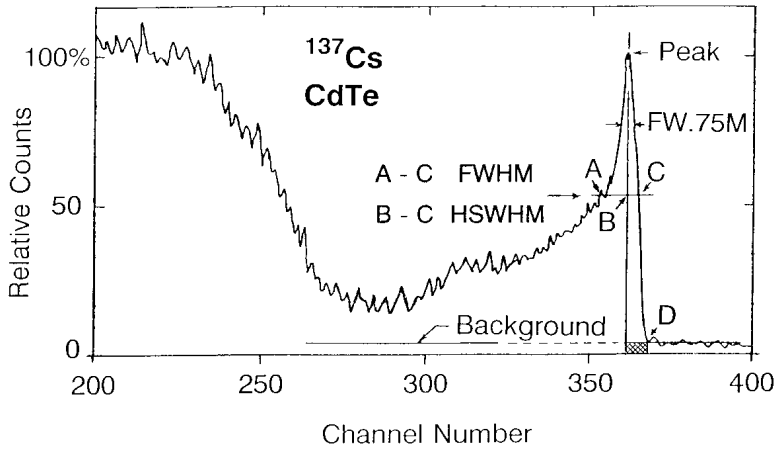


Figure 5—Unenhanced, full-energy peak gamma-ray peak, ^{137}Cs. The FWHM, FW.75M, HSWHM, the high-side area, and the background are illustrated.

a) Tailing is present in the spectrum of a monoenergetic peak when FW.25M > $\sqrt{2} \cdot$ FWHM (Annex C).
b) FW.75M, FWHM, and HSWHM are labelled in the figure.
c) The intensity of the background (if any of significant intensity is present and whatever its shape) is regarded as the counting rate averaged over the five to ten channels above the high-side toe (D), as indicated by the line labelled *background*.

5.4 High-side area (HSA)

If tailing obscures the low-side toe, as illustrated in Figure 5, the total area of the peak cannot be defined; as stated above, the efficiency specification shall then depend on the HSA, and it shall be made clear in the specification that the HSA is the area being used.

In Figure 5, the HSA is bounded by two features:

a) At the low-energy side, by the peak center line;
b) At the high-energy side, by the toe of the peak, D;

The background under the HSA is the shaded region, which is bounded by the peak center line, the ordinate at the toe (D), the background line, and the abscissa.

Note—If there were no low-side tailing, the HSA would be exactly half of the full area of the peak.

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5.5 Peak-to-valley ratio

The peak-to-valley ratio is defined for WBG detectors as the ratio of the amplitude of the peak to the amplitude of the tail at specified energy values and is thus an indication of the quality of the detector, as are also the detector performance characteristics of 6.6 and measurements in Clause 10. Clause 12 discusses peak-to-valley measurement.

6. Specifications

If the detector is a stand-alone device, the manufacturer is expected to furnish the specifications listed in this clause. If the detector is part of a packaged system which will be used to obtain spectra, the manufacturer is expected to furnish, as a minimum, the energy resolution (see 6.6), efficiency (see 6.6), and the permissible range of operating temperature [see a) in 6.5]. Other characteristics can be specified by agreement between the user and the manufacturer. (See Clause 7, Clause 8, and Clause 9 for the methods of measurement.)

6.1 Geometry and packaging

The following shall be given:

a) Detector geometry (planar, hemispherical, other);
b) Packaging details, including the types of connectors, if furnished;
c) Dimensions of the active volume of the detector;
d) Nature of the contacts (optional).

6.2 Detector capacitance

For stand-alone detectors:

a) The capacitance shall be given at the recommended operating voltage;
b) The method used to make the measurement shall be specified;
c) If a bridge method is used, the operating frequency shall be given.

6.3 Detector bias

Specifications shall be given for:

a) Maximum permissible detector bias;
b) Recommended operating bias.

If the detector geometry requires special biasing (detectors with field-forming electrodes, pixel detectors, multi-strip detectors), that biasing shall be specified.

6.4 Leakage current

For stand-alone detectors, the leakage current shall be given at:

a) Maximum permissible detector bias;
b) Recommended operating bias [see also c) in 6.5];
c) The detector temperature at which the measurements were made.

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6.5 Temperature operating range and temperature sensitivity

The following temperature information shall be given:

a) Recommended operating range;
b) Temperature coefficient of pulse height over the range 20 °C – 50 °C (i.e., % change/°C in the position of a reference peak);
c) Leakage current (% change/°C of the leakage current).

6.6 Detector performance

The performance characteristics listed below shall be given for full-energy peaks in the energy range for which the detector is designed. It is desirable for the peaks to be monoenergetic, but if they are not, the separation between the peaks shall be great enough to permit the performance figures to be given unambiguously (i.e., the influence of possibly interfering peaks shall be less than the stated accuracy of the specification).

a) FWHM (and/or HSWHM)
b) FW.25M
c) FW.1M (if measurable)
d) Counting efficiency based on the HSA and, in the absence of tailing (see 3.1.92, Figure 2, and Figure 5), the full area of the peak

6.7 Test sources

The spectral peak commonly used for testing energy resolution of a detector is the 122 keV line of ^{57}Co. At this energy, the efficiency of the detector is sufficient to obtain the necessary counts in a reasonable time. Other energies are also used to describe the measured parameters as a function of energy. In the interest of standardization, it is desirable that everyone use the same radionuclides for resolution tests.

Recommended radionuclides for calibrating and testing a spectrometer are given in Table 2.

If the detector is encapsulated, the manufacturer shall give the distance between the window of the encapsulator and the facing surface of the detector element.

Different sources are used for different tests. The point source is used for the resolution and relative efficiency measurements (all done at 25 cm distance). The extended flat source is used for absolute efficiency measurements in close geometries. The extended source is typical of the actual measurement geometries used in most experimental situations. The absolute efficiency measurements using extended sources will be more indicative of the expected results than just the single point source measurement.

Currently (2001), the high-energy efficiency for these detectors is low. The higher energy sources are listed for possible future use.

6.7.1 Point source

6.7.1.1 Form

A standard point source is usually prepared in the form of a disc upon which the radionuclide is deposited in solid form, usually by evaporation from solution.

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Table 2—Radionuclides for energy resolution and other measurements

Radionuclide	Half-life		Energy	
^{55}Fe	2.74	Years	5.90	keV[a]
^{241}Am	433.00	Years	59.54	keV[b] and 26.3 keV X rays
^{109}Cd	463.00	Days	22.20	keV[c] and 88.0 keV[d] (X ray doublet)
^{57}Co	272.00	Days	122.10	keV[e] and 136.5 keV
^{137}Cs	30.20	Years	661.70	keV[f g]
^{60}Co	5.27	Years	1173.2	keV and 1332.5keV[h]

[a]Gamma and X-rays recommended for energy resolution and efficiency measurements.
[b]See Footnote a.
[c]See Footnote a.
[d]See Footnote a.
[e]See Footnote a.
[f]See Footnote a.
[g]X-rays with energies of 31.8, 32.2, and 36.4 keV are produced by the ^{137}Ba daughter.
[h]See Footnote a.

Discs made of high atomic number materials (metals) should be avoided because of Compton effects. In this standard, a point source is defined as a disc in which the diameter of the active region of the radionuclide is ≤ 2 mm. (The thickness of the active material is essentially zero; an active region 2 mm in diameter is so small that the solid angle of the photons intercepted by the detector element is nearly independent of where in the source the photons originate.)

6.7.1.2 Source placement

A point source shall be (a) located axially with respect to the detector element, (b) 25 cm from its face, (c) with the plane of the source parallel to the face of the detector element, and (d) with nothing but air between the source and the detector assembly.

High-atomic number objects (e.g., shields and supports) in the vicinity of the setup can scatter photons into the detector element. Those objects shall be small enough or far enough away so that the photons scattered into the detector are ≤ 2% of the direct beam from the source.

6.7.2 Extended flat source

6.7.2.1 Form

An extended flat source is usually prepared by uniformly depositing the radionuclides to completely cover a given circular or rectangular area. For a thin source, the radionuclides may be deposited in a uniform pattern of small, closely spaced, point sources. The source material layer is usually a thin single layer of material such as filter paper or plastic film. It is possible to layer other materials both between the active layer and the detector and on the reverse side. For thick sources, the radioactive fill material can be molded or cast in the desired shape.

Substrates made of high atomic number materials (metals) should be avoided because of Compton effects. In this standard, the dimensions of the active region of the radionuclides are the maximum extent of the actual radionuclide deposit.

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6.7.2.2 Extended flat source placement

A flat extended source shall be (a) located axially with respect to the detector element, (b) at the specified distance from its face, usually directly on the detector housing, (c) with the plane of the source parallel to the face of the detector element, and (d) with nothing but air between the source and the detector assembly.

High-atomic number objects (e.g., shields and supports) in the vicinity of the setup can scatter photons into the detector element. Those objects shall be small enough or far enough away so that the photons scattered into the detector amount to ≤ 2% of the direct beam from the source.

6.8 Source types

Source types 6.8.1, 6.8.2, 6.8.3, 6.8.4, 6.8.5, and 6.8.6 are based on and consistent with 10.7.1–10.7.6 in IEEE Std 325-1996.

6.8.1 Certified source

A certified source is a source that has been calibrated for photon emission rate[8] at specified energies by a laboratory recognized as a country's national standardizing laboratory for radioactivity measurements[9] and has been so certified by the calibrating laboratory.

6.8.2 Calibrated source

A calibrated source is a source that has been calibrated by comparing its photon emission rate to that of a certified source.

6.8.3 Certified-solution source

A certified-solution source is a volume source that contains a certified solution as its radioactive filling material.

6.8.4 Calibrated-solution

A calibrated-solution source is a volume source that contains as its radioactive filling material a solution that has been calibrated by comparing its photon emission rate at specified energies to that of a certified solution

6.8.5 Certified solution

A certified solution is a radioactive material in liquid form that has been calibrated and certified by a laboratory recognized as a country's national standards laboratory for radioactivity measurements.

6.8.6 Radioactive filling material

Representative radionuclides for use in calibration sources are listed in Table 2. The carrier shall have an effective atomic number (Z) of 4.0 ± 0.7 and a mean specific gravity of (1.15 ± 0.02) g cm^{-3} for solid carriers, or (1.06 ± 0.01) g cm^{-3} for liquid carriers. The density of the carrier shall be stated so that attenuation corrections may be made. The source activity shall be below the level that produces a corrected dead-time loss of not over 2% in the counting system.

[8]International Commission on Radiation Units and Measurements, Certification of Standardized Radioactive Sources, ICRU Report No. 12, Sept. 15, 1968.

[9]For the U.S., the U.S. National Institute of Standards and Technology is the certifying laboratory.

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The solid carrier is preferred for general use because it is in the form of a safe, chemically inert, sealed source.

6.9 Source documentation

A certificate shall be provided with each source stating whether it is a certified source or a calibrated source. ln the case of the certified-solution source and the calibrated-solution source, the certificate shall be for the solution alone. The certificate shall contain the following information:

a) Radionuclides used and calibrated together with
   1) The photon energies and radionuclide half-lives;
   2) Dates corresponding to the stated photon emission rates;
   3) Uncertainties in the stated photon emission rates; in the case of a calibrated source that has been calibrated against a certified source, the uncertainties for each shall be given separately; in the case of a calibrated-solution source that has been calibrated against a certified-solution source, the uncertainties for each shall be given separately;
   4) Density of the carrier;
b) Calibration dates: In the case of a source calibrated against a certified source, the dates of calibration of each shall be given; in the case of a calibrated-solution source calibrated against a certified solution, the dates of calibration of each shall be given;
c) Full genealogy in the case of a calibrated source or a calibrated-solution MBSS (see 10.6 of IEEE Std 325-1996), including identification of the certified source or certified solution against which it has been calibrated;
d) Calibrating laboratory or organization.

6.10 Timing properties

It is recommended that the following detector timing properties be given:

a) For detectors with planar geometry, the maximum electron collection time as measured at the output of the preamplifier (Waveform 1 in Figure 4), the value to be corrected for preamplifier risetime.
b) For detectors with nonplanar geometry, the 10%–90% risetime of maximum-amplitude pulses measured at the output of the preamplifier, corrected for preamplifier risetime.

7. Spectrometer setup

The block diagram of a typical spectrometer appears in Figure 6. The components are described in the following subclauses.

7.1 Instrument grouping

Test setups as shown in Figure 6 are vulnerable to electromagnetic (E-M) interference from sources external to the measuring system. To minimize it:

a) All components of the system must be as physically close together as possible, and if operated from the power line, plugged into a single outlet box which in turn is powered from a wall outlet;
b) Interconnecting cables should be ≤ 2 meters long and bundled together.

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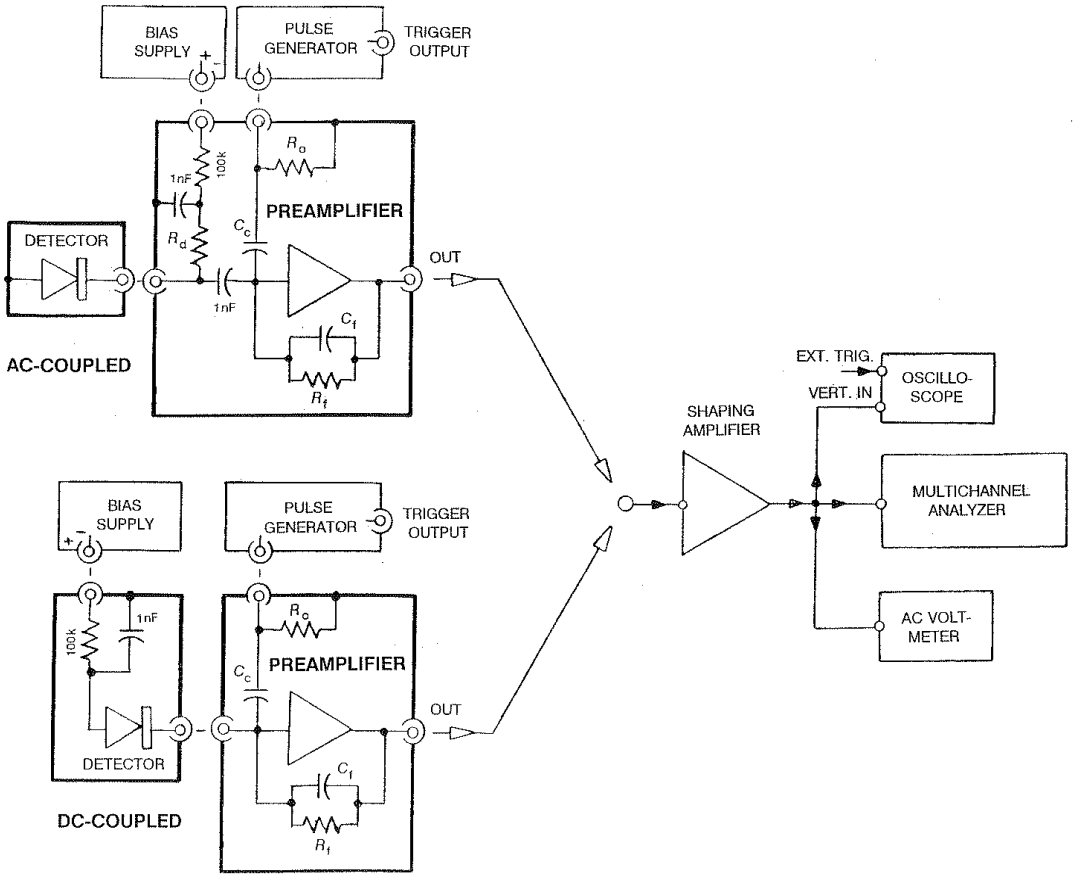


Figure 6—Block diagram of a spectrometer

Tests for interference and the means of reducing it are described in Annex B. The procedures given there shall be applied whenever there is a change in the components of a test system or in its arrangement.

7.2 Detector and preamplifier

It is assumed that the detector, shown as a reverse-biased diode in Figure 6, is connected to a charge-sensitive preamplifier, either by ac- or dc-coupling (see 3.1 and IEEE Std 301-1988). AC-coupling is shown in the blocks at the upper left, dc-coupling in the blocks below.

a) DC-coupled preamplifiers, because they have fewer components that degrade the noise performance, may be preferred, but their steady-state count-rate tolerance is lower than that of ac-coupled units (IEEE Std 301-1988);
b) Reset-type preamplifiers combine the advantages of ac- and dc-coupled units and eliminate the need for a P/Z cancellation network in the main amplifier, but the system must be designed to accommodate the effects of the reset waveform. A setup showing a reset-type charge-sensitive preamplifier is described in IEEE Std 325-1996.

7.3 Shaping amplifier (main amplifier)

There are many shaping amplifiers available from commercial sources. The characteristics, except for those specifically affecting the tests described herein, are not dealt with here (see IEEE Std 301-1988).

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7.4 Pulse generator (pulser)

The width of a spectral line (energy resolution) is the quadratic sum of detector resolution and the electronic noise of the spectrometer. The latter can be determined with the use of a precision pulser (see 3.1) as described in 10.1. Also, the pulser, in conjunction with an accurate step attenuator (built-in or external), affords a precise way of checking the dc offset of the analog-to-digital converter (ADC) (see 8.3).

Whether or not the pulser may be left on during measurements of radiation depends on the pulser design.

a) If the pulser produces a square wave, the waveform transition to the polarity opposite that produced by the detector can disrupt the operation of the main amplifier's baseline restorer (BLR) unless the amplifier was specifically designed to accommodate such a transition (as is the case for systems meant to operate with reset-type preamplifiers);
b) If the generator produces a tail pulse (see 3.1), the output signal from the main amplifier will exhibit an undershoot
    1) The undershoot occurs because the decay of the pulser signal has the same effect as adding a second differentiator to the amplifier;
    1) P/Z cancellation can remove the undershoot due to the preamplifier or pulser decay constants, but not both. Detector pulses that occur during the undershoot will have their amplitudes depressed, resulting in spectral peaks with low-side tails. This can be avoided by turning off the pulser during runs made to determine detector resolution.

7.5 ADC and multichannel analyzer (MCA)

ADCs are available as modules intended for use with computers, or they can be an integral part of an MCA. In both configurations, the ADC/MCA is programmed to display all or several of the following characteristics of spectral lines:

a) Address of the peak channel (as a channel number and/or as an energy);
b) Counts in the spectral line (i.e., the area between the low- and high-energy toes);
c) Counts in the peak channel;
d) Provisions for automatic background subtraction.

Those programs should be checked when an ADC/MCA is first put into service. Of special concern is how the programs respond to peaks with low-side tails.

8. Zero settings and calibration

At the initial setup and periodically thereafter (daily, weekly, or monthly according to the history of drift rates), the zero settings and calibration of the pulser, main amplifier, ADC, and oscilloscope shall be examined and corrected according to the methods given in their instruction manuals. However, the following procedures have proved useful and efficient for removing zero offsets in the pulser, amplifier, and ADC.

8.1 Zero offset, pulse generator

The procedure described in this subclause applies only to pulsers in which

a) A multiturn potentiometer is used for pulse-height adjustment;
b) That potentiometer spans the range from zero to maximum output; and
c) The dial has a mechanical adjustment for its zero setting.

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A switchable x2 attenuator in the pulser is required. Usually that attenuator is built in, but whether it is or not

d) If the zero is to be set to be within ± 1 channel per thousand, the resistors in the x2 attenuator section must have a tolerance of ≤ ± 0.1%.
e) If the setting is to be within ± 0.1 channel, the tolerance must be ≤ 0.01%.
f) The preceding does not apply to the terminating resistor at the receiving end of a connecting cable; it may have any value without affecting the x2 factor. (However, the *absolute* value of the output voltage is affected by the accuracy of the terminating resistor: if its error is ε%, the error in the absolute voltage will be (ε/2)%.)

The procedure is as follows:

g) Switch in the x2 attenuator;
h) Set the pulser dial to full scale and the amplifier gain control to a level that places the peak in a high-numbered ADC channel;
i) Reset the pulser dial to precisely half its original setting and switch out the x2 attenuator.

The peak position should not have moved. If it has, trim the mechanical zero of the generator dial to produce half of the original error in the peak position, but in the opposite direction of the peak shift. (Trimming the zero setting may require loosening the knob's set screw and turning the knob on the potentiometer's shaft.)

j) Repeat the test until the peak position remains stationary during the switching routine.

8.2 Zero offset, amplifier

Adjust the amplifier offset before adjusting the ADC offset.

In the absence of input signal and with a dc voltmeter connected to the output terminal of the amplifier, adjust its offset control to reduce the offset to ≤ 0.1 channel width.

Example: For a 1k ADC having a full-scale range of 8V, the channel width is (8V)/(1000 Channels) = 8 mV; the amplifier offset should be ≤ 0.8 mV.

8.3 Zero offset, ADC

In the setup of Figure 6 and in the absence of a radioactive source

a) Set the x2 attenuator switch to the OUT position;
b) Adjust the amplifier and pulser to center a peak in an even-numbered channel near the top of the ADC's range. Note the channel number.
    1) Note: Set the main amplifier gain low enough so that noise modulation of the peak is #1 channel.
c) Switch in the x2 attenuator. Note the channel number to which the peak has moved. It should be precisely half of the original one. If it is not
    1) Note the error in channel numbers,
    2) Return the system to its initial settings;
    3) Trim the offset control until the peak shifts by half of the noted error, but in the direction *opposite* to the error;
    4) Repeat the test. (If the ADC has automatic offset control, this test will measure its accuracy.)
d) Move the initial peak position to the middle of the ADC's range (e.g., Channel No. 2,000) by halving the output of the pulser. The peak should move to the center of Channel No. 1,000.

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If this last condition is not met, the most likely cause is integral nonlinearity of the amplifier, ADC, or both. Because the region of nonlinearity usually occurs near the top of the dynamic range, it may prove useful to limit measurements to the lower 80% of the range.

e) Example
   1) Peak position initially centered in Channel No. 4,000;
   2) Switch in the x2 attenuator. It is observed that the peak moves to Channel No. 1,996 when it should be 2,000. The error is –4.0 channel;.
   3) Switch out the x2 attenuator, and trim the offset control to move the peak upwards by two channels (half the error, in the opposite direction of the error);
   4) Trim the amplifier gain control or the pulser output to move the peak back to Channel No. 4,000;
   5) Repeat the procedure until the Step 2 condition is met. (Usually, the first iteration is sufficient.)

9. Measurements

9.1 Detector leakage current

Detector leakage current can be measured directly or it can be measured by noting the offset produced in a dc-coupled preamplifier.

9.1.1 Leakage current, direct measurement

Some detector bias supplies have a built-in ammeter or means for connecting an external one. If neither of these options is available, a battery operated electronic ammeter (preferred) can be connected in series with the detector, either on the grounded side or floated at the high-voltage terminal of the bias supply.

Bypass the ammeter with a 0.1 μF ceramic capacitor at the point where it is connected in the circuit.

9.1.2 Leakage current, measurement with the preamplifier

The detector shall be dc-coupled to the preamplifier.

a) Remove all radioactive sources and apply normal bias to the detector;
b) Measure and record the dc output voltage of the preamplifier (V_1);
c) Replace the detector by a low-loss capacitor of approximately the same capacitance as that of the detector (low loss meaning dielectrics of porcelain, plastic-film, or NPO or CGO ceramic);
d) Measure and record the output voltage of the preamplifier (V_2);
e) The detector leakage current can then be computed from Equation (1):

$$I = (V_1 - V_2)IR_f \quad (1)$$

where:

I is the current (amperes),
R_f is the value of the preamplifier feedback resistor (ohms).

Note—$V_1 - V_2$ shall be less than 10% of the preamplifier's dynamic range. If it is more, R_f shall be replaced with a resistor that meets the 10% criterion.

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9.2 Capacitance measurement

Detector capacitance can be measured with a bridge, LC meter, or with a pulser and an ac-coupled, charge-sensitive preamplifier. In all cases the measurement shall be made with normal bias voltage applied to the detector. With a preamplifier, its built-in biasing network can be used; with a bridge or LC meter, a test fixture is required that allows bias voltage to be applied to the detector while capacitively isolating it from the bridge or LC meter (middle block of Figure 7).

a) The size of R_d shall be chosen such that the voltage drop across it (produced by the detector leakage current) shall be less than 5% of the applied bias voltage;
b) The ac voltage applied to the detector from the bridge, the pulser, or the LC meter shall be less than 5% of the bias voltage;

Caution—When an external biasing network is used (middle block of Figure 7), to prevent damage to follow-on circuits, short the output connector before applying or disconnecting the bias voltage.

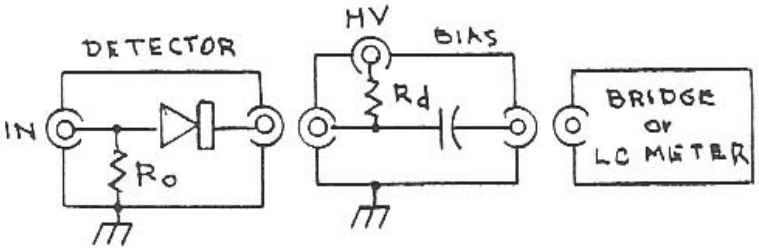


Figure 7—Detector and detector-bias fixtures. R_o in the detector fixture is a pulser terminating resistor.

9.2.1 Capacitance measurement, preamplifier

Measuring capacitance with a preamplifier consists of applying a pulser signal, first to the test input of the preamplifier (Figure 6), then to the IN terminal of the detector (Figure 7). The detector capacitance can then be computed as a multiple of the preamplifier test-input capacitance C_c (Figure 6), where the multiple is the ratio of pulser voltages necessary to maintain a fixed output signal from the main amplifier. *With this test method, the capacitance of the connectors do not add to the measured capacitance of the detector.* The procedure is as follows:

a) The preamplifier shall be ac-coupled (upper block in Figure 6);
   1) The biasing network in Figure 7 (middle block) should not be used because it duplicates the one in Figure 6.
b) Ground the detector input terminal through a terminating resistor R_o having the same value as the one at the test input of Figure 6 (± 1%);
c) Apply normal bias voltage to the detector;
d) Inject a pulser signal to the preamplifier's test input connector and adjust the system to produce a convenient reference pulse at the output of the main amplifier as measured with an oscilloscope or MCA. Note the pulser voltage, V_1;
e) Move the pulser to the input of the detector fixture and readjust its voltage to obtain the same pulse height as in the preceding step. The new pulser voltage is V_2.

The detector capacitance C_d is shown in Equation (2):

$$C_d = (V_1/V_2)C_c \quad (2)$$

where the terms are defined in the preceding text.

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9.2.2 Capacitance measurement, bridge, and LC meter

a) Both detector and detector-bias fixture shall be used, but a pulser is not required;
b) Short-circuit the IN terminal of the detector fixture;
c) The capacitance measurement must be made in two steps:
   1) With the detector disconnected, C_1,
   2) Then with the detector connected, C_2;
d) The detector capacitance is then $C_2 - C_1$;
e) *The capacitance so measured includes that of the detector connector.*

9.2.3 Capacitance measurement, bridge

An accurate measurement of capacitance depends on obtaining a perfect null at the bridge operating frequency. (Distortion may produce low-level harmonics at and near the null, but these may be ignored.)

a) At low frequencies, R_d and the parallel resistance of the detector may cause difficulty in obtaining the null;
b) At high frequencies, the series resistance may cause such a difficulty.

The balance will be easiest to obtain at some intermediate frequency which is best set by trial and error. Over at least a 2:1 frequency range at an operating frequency that allows a perfect null to be obtained, the measured capacitance should be independent of the frequency.

9.2.4 Capacitance measurement, LC meter

a) With the bias fixture disconnected from the bridge or LC meter, measure the capacitance C_1;
b) Connect the fixtures, apply normal bias voltage to the detector, and measure the capacitance C_2.

The detector capacitance, *which includes the capacitance of the output connector of the detector fixture,* is $C_2 - C_1$.

10. Measurement of energy resolution

Energy resolution is discussed in 5.3, and the parameters to be measured, in 6.6. Additional details of the measurements are given in this clause.

a) The instrumentation shown in Figure 6 shall be used for the measurements, with the test source (6.7.1, 6.7.1.1, 6.7.1.2, 6.7.2, 6.7.2.1, 6.7.2.2) being a disc located 25 cm from the detector with the active region of the source contained within a circle of diameter not more than 2 mm.
b) For peaks exhibiting little or no low-side tailing (Figure 3), measurements of FWHM shall be made.
   1) There shall be at least 5 channels across the FWHM and at least 10,000 counts in the peak channel;
c) For peaks exhibiting low-side tailing so severe that the FWHM is meaningless (Figure 2), a measurement of the HSWHM shall be made.
   1) There shall be at least 2.5 channels across the HSWHM and at least 10,000 counts in the peak channel;
d) The height of the peak shall be measured from the level of the background to the peak center line as defined in 3.1.
   1) For a peak with severe low-side tailing, the background is considered to be the average intensity of the 5 to 10 channels higher than the high-side toe (D in Figure 5).
   2) For a peak with little or no low-side tailing (e.g., the peak at 32 keV in Figure 3), the high-side background is the average intensity of the 5 to 10 channels higher than the high-side toe (in the figure, the region between 33.2 and 35 keV), and the low-side background is the average

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intensity in the 5 to 10 channels of the plateau region lower than the low-side toe (the region between 24 and 27 keV). The background under the peak shall be considered to be the average of the two backgrounds just described.

Resolution values can be identified as follows at half the peak maximum height (HM):

— FWHM (full width at half maximum)
— HSWHM (high-side width at half maximum)
— 2xHSWHM (two times high-side width at half maximum)

The resolution 2xHSWHM will be essentially the FWHM where suitable enhancement techniques are employed, either within the detector or externally. The same applies at other than half-maximum height, such as FW.1M or FW.04M. (See 6.6.)

Useful relevant information will be found in Clauses 6 and 7 of IEEE Std 325-1996.

The peak shape for these detectors can be very different from detector to detector. The methods described here cover the range of peak shapes from these detectors.

10.1 Noise line width

The energy resolution of a spectrometer is the quadratic sum of the detector resolution and the electronic noise of the system, as shown in Equation (3):

$$\Delta E_t = [\Delta E_d^2 + \Delta E_n^2]^{1/2} \quad (3)$$

where

ΔE_t is the measured resolution,
ΔE_d is the resolution of the detector in the absence of electronic noise,
ΔE_n is the noise line width.

Electronic noise arises from leakage current in the detector, the input transistor of the preamplifier, and all resistors connected to its input, including the ohmic resistance of the detector contacts and the resistance of any dead layer the detector element may have.

In principle, the electronic noise can be measured with an ac voltmeter, but in practice, this is usually impractical. The difficulty is that the BLR suppresses low-level signals (such as electronic noise), requiring the BLR to be inactivated. This may not be possible without modifying the main amplifier. Instead, ΔE_n should be determined by measuring the width of the peak produced by a pulser. The pulser peak should be located just above the full-energy peak produced by the test source. Then, by rearranging terms in Equation (3):

$$\Delta E_d = [\Delta E_t^2 - \Delta E_n^2]^{1/2} \quad (4)$$

This measurement is meaningful only if the noise line width of the pulser is less than half of the system's electronic noise. This can be tested by reducing the amplifier gain by a factor of ten while increasing the output of the pulser by the same factor, thereby causing the pulser noise to dominate. (The line width so obtained should meet the criterion stated in the preceding sentence.)

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11. Efficiency measurements

11.1 Gamma-ray counting efficiency for a full-energy peak

With the setup shown in Figure 6, obtain a spectrum using a calibrated point source as described in 6.7.1.

For an encapsulated detector, it shall be stated whether the face refers to the detector element or to the window of the detector package.

If the spectrum exhibits a ratio of FW.1M to FWHM ≤ 2.0, with or without resolution enhancement, Equation (5) shall be used to compute its efficiency (see 5.2, 5.3):

$$\eta_a = 100 \cdot [A_s / N_s] \quad (5)$$

where:

η_a = counting efficiency (%),
A_s = area of the peak (counts), less background,
N_s = total number of full-energy photons emitted by the source during the live counting time.

If the spectrum exhibits a ratio of FW.1M to FWHM > 2.0, Equation (6) shall be used to compute the efficiency:

$$\eta_{ah} = 2 \times 100 \times [A_h / N_s] \quad (6)$$

where:

η_{ah} = high-side based counting efficiency (%),
A_h = area of the high side of the peak (counts), less background (see 5.4 regarding the high-side area),
N_s = total number of full-energy photons emitted by the source during the live counting time.

This efficiency figure shall be referred to as the *high-side based counting efficiency* (η_{ah}). For a detector free of low-side tailing, η_{ah} [Equation (6)] is the same as η_a [Equation (5)].

12. Peak-to-valley ratio

The peak-to-valley ratio (see 5.5) shall be measured at energies on the low side of the peak at energies distant 0.5 x FWHM, 2 x FWHM, and 5 x FWHM from the center line of the peak, unless these positions correspond to peaks in the spectrum from any cause, such as escape peaks.

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Annex A

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Annex B

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Electromagnetic interference

B.1 Pickup, E-M radiation

The connecting cables between components of a system, if spread out, act as antenna loops that can pick up E-M radiation. (Another way of looking at this is that those loops act as the secondary of a transformer into which a varying magnetic field will induce a voltage, therefore a current.) It would seem that the coaxial cable sheath would prevent such signals from getting into the system, but the shield braid has openings in it, and the impedance of the braid is finite, limiting its effectiveness. Cables with a double outer shield (e.g., RG55B/U instead of RG58C/U) are 10 times more effective in reducing pickup than singly shielded cable.

Cables should be bundled to minimize the areas of such loops, and cables longer than the shortest one in the bundle should be folded back and forth upon themselves before bundling.

B.2 Ground-loop noise

A *ground loop* is set up when two components of a measuring system are plugged into two electrical outlets several meters apart. (There can also be ground loops independent of the power-line connections that result from the interconnections between instruments). How such loops make the system vulnerable to noise pickup is illustrated by the following.

The resistance of a 100 W lightbulb connected to a 115 V power line is ≈ 100 Ω at normal operating temperature, perhaps 25 Ω when cold. The characteristic impedance of the usual power line is ≈ 100 Ω. When the bulb is switched on, a 25-Ω load is suddenly connected to a source with an internal impedance of 100 Ω. A step of voltage is produced—V = 115 A [25/(100 + 25)] = 21 V—that propagates along the power line. The wavefront, as it passes between the power outlets to which the instruments are connected, produces a 21-V transient voltage difference between them. With a propagation velocity of ≈ 0.6 c = 1.8 x 10^8 meters/s, a 21-V spike is produced having a width of 5.5 ns per meter of separation between the outlets. The resulting current flow along the outer shield of the signal cable connecting the two instruments, multiplied by the impedance of that shield, produces an unwanted voltage spike that appears in series with the desired signal.

The simplest way of avoiding the preceding situation is to plug the power supplies of all parts of the system into one outlet box, which is then plugged into a single electrical outlet.

Some ground loops within the instrument chain may be unavoidable, such as the one produced when the signal output of the test-pulse generator is connected to the preamplifier (through the test-pulse capacitor), and the trigger output is connected to the oscilloscope trigger-input terminal. The effect of such a loop can be reduced through the use of ferrite cores.

It should also be noted that the NIM bin housing comprises a one-turn loop that acts as the secondary winding into which the stray magnetic field from the power transformer induces a current. The result is a difference in ac potential between various parts of the bin that can find its way into the signal path [see c) in B.3.2.]

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B.2.1 Ferrite cores

The effect of ground loops can be reduced by threading several turns of one of the connecting cables, or the power cord to that module, through a ferrite core. (Suitable cores are available from electronic supply houses. The best ones are high-permeability toroids large enough to allow a power plug to be passed through.) This increases the impedance of the ground loop by an amount proportional to the square of the number of turns and reduces the circulating current. (The resulting voltage drop between the ends of the cable does not appear as a *difference* signal between inner and outer conductors, therefore does not appear as an interfering signal).

Some MCAs, particularly those comprising an ADC and a computer, can generate ground-loop noise. When that occurs, it may be possible to eliminate it by isolating the connection to the amplifier through the use of a ferrite core.

B.3 Examination for external noise pickup

Examination for external noise pickup must proceed in steps, beginning with an instrument chain comprising:

a) The detector (sans test source, but with its bias supply). The detector must be shielded to minimize response to background radiation;
b) Preamplifier and main amplifier;
c) Clipping network (Figure B.1);
d) Oscilloscope (dc coupled, sans probe).

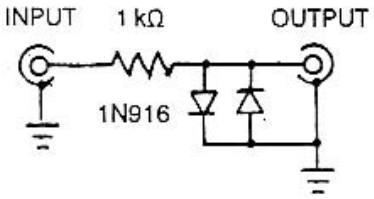


Figure B.1—Clipping network

All other instruments must be disconnected, both from the signal chain and the power line.

B.3.1 Clipping network

A clipping network must be plugged into the input of the vertical amplifier of the oscilloscope to prevent detector background pulses from overloading it. (This network can be built into a small, commercially available fixture box. Any gold-doped silicon signal diode or Shottky diode may be used in place of the 1N916. The 1 kΩ resistor may be 1/4 W, ± 10%. The oscilloscope input resistance must be at least 100 kΩ).

B.3.2 Initial settings

a) The oscilloscope amplifier should be set for a sensitivity of ≈ 50 mV/cm, dc coupled.
b) The oscilloscope sweep should be internally triggered, dc coupled.
c) Unless the main amplifier's input and output connectors are electrically isolated from the panels, external connections to them must both be at the front panel or both at the rear (see B.2, last paragraph).
d) The main amplifier gain should be set to produce a noise band ≈ 1 cm high.

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B.3.3 Noise search

a) Beginning with the oscilloscope sweep trigger set for minimum sensitivity, advance it until it triggers on the detector background pulses, which should be ignored. The search must be for (1) spikes that appear above the steady noise level, and (2) sine waves. To find these, if present, it will be necessary to change the sweep speed over a wide range.
b) If sine waves appear, they may be due to a local radio station. The indication is a carrier accompanied by audio modulation.
c) If spikes appear, trigger the sweep from the power line and repeat the search. If the spikes are synchronized with the power-line frequency, the spike pattern will be stable and may be caused by fluorescent lights. If that is the case, and the pickup is not due to illumination of the detector, it may be necessary to use a power-line filter or a regulating power transformer for the instrument setup, which is advisable in any case.
d) If the main amplifier is plugged into a NIM bin, other instruments in the bin—including a plug-in power supply if one is being used—may be the source of the noise. In this instance, the amplifier and power supply should plugged into opposite ends of the bin.

B.3.3.1 Pulse generator and oscilloscope

If the system is “clean,” the next step is to connect the pulse generator to the preamplifier test input and to the external-trigger input of the oscilloscope, and to repeat the preceding tests. If spikes appear, they may be due to the ground loop set up by the connection of the generator. This loop can be broken through the use of a ferrite core (see B.2.1).

B.3.3.2 MCA

Finally, the MCA shall be connected, the test source mounted at the detector, and the system adjusted to place the peak at the desired channel number. The source should then be removed, and without altering the amplifier controls, the earlier search for noise spikes shall be repeated, with and without the ADC in the count-accumulation mode.

There should be no change in the spike pattern or in the ac voltmeter indication between the two modes, or with the MCA disabled. If the MCA introduces noise, isolation of its input cable and/or its power cord with ferrite cores may help.

B.4 Summary

The preceding routine should make it possible to rid the system of external electrical noise. Trial and error in applying the routine is inevitable. The amount of time required to produce a quiet system will depend on the environment. In a very noisy one, it may help to ground the system to a cold water pipe (or to some other ground) through 1-cm wide copper braid. The braid connection to the system shall not be made at the detector or the preamplifier, but to a point near the output end of the signal path. In fact, for safety reasons, grounding will be necessary if an isolating transformer is used that breaks the normal ground connection through the power cable.

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Annex C

(informative)

Full width at y maximum (FWyM)

The shape of an ideal peak is $y = \exp{-(1/2)[(x - x_o)/\sigma]^2}$. The peak occurs at $x = x_o$ and has a maximum value of $y = 1$. Of interest are

a) The full width of the peak at various values of $y < 1$ (FWyM)
b) The high-side widths at those values (HSWHM; these are FWyM/2)
c) The ratio of FWyM to FWHM at these values

The values listed in Table C.1 are for various values of y. Note that if tailing is present, the measured ratio of FWyM to FWHM (last column) will be greater than the indicated values.

Table C.1—Parameters for a normal distribution for $\sigma = 1$

y	FWyM	HSWyM	FWyM	$\frac{\text{FWyM}}{\text{FWHM}}$
0.7500	FW.75M	0.7585	1.5171	0.644
0.6053[a]	—	1.0000	2.0000	1.201
0.5000	FWHM	1.1774	2.3548	1.000
0.2500	FW.25M	1.6651	3.3301	1.414[b]
0.1000	FW.1M	2.1460	4.2919	1.822
0.0500	FW.05M	2.4470	4.8555	2.079
0.0200	FW.02M	2.7972	5.5944	2.376
0.0100	FW.01M	3.0349	6.0697	2.578

[a] $y = e^{-1}$
[b] This is $\sqrt{2}$.

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